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X-ray absorption spectroscopy and x-ray magnetic circular dichroism of epitaxially grown Heusler alloy Co$_2$MnSi ultrathin films facing a MgO barrier

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We element specifically studied the electronic and magnetic states of epitaxially grown full-Heusler alloy Co$_2$MnSi (CMS) 1.1 nm (4 ML) thick ultrathin films facing an epitaxial MgO(001) tunnel barrier by means of x-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD). In situ reflection high-energy electron-diffraction observations indicated that the CMS films grew into the L$_2^1$ structure. The observed XAS and XMCD spectra revealed that the CMS ultrathin film was not oxidized. The ratio of Mn and Co spin magnetic moments obtained by applying the sum rules was about 2.7, close to a theoretical value of 2.8 for CMS with the L$_2^1$ structure. © 2007 American Institute of Physics. [DOI: 10.1063/1.2824856]

Co-based full-Heusler alloys (Co$_2$YZ) have attracted much interest as a desirable ferromagnetic electrode material for spintronic devices. This is because of their potentially high spin polarization arising from the half-metallic ferromagnetic nature theoretically predicted for some of these alloys, and because of their high Curie temperatures, which are well above room temperature (RT). Some of the present authors recently developed fully epitaxial tunnel junctions (MTJs) with a Co$_2$YZ thin film of Co$_2$Mn$_{0.91}$Si$_{0.93}$ (CFCA), Co$_2$MnSi (CMS), or Co$_2$MnGe as a lower electrode and a MgO(001) tunnel barrier, and demonstrated relatively high tunnel magnetoresistance (TMR) ratios of 109% at RT (317% at 4.2 K) for CFCA/MgO/Co$_2$Mn$_{0.91}$Si$_{0.93}$ MTJs (Ref. 4) and 90% at RT (192% at 4.2 K) for CMS/MgO/Co$_2$Mn$_{0.91}$Si$_{0.93}$ MTJs. The electronic and magnetic states of the interfacial region of ferromagnetic electrodes with a tunnel barrier play an essential role in the spin-dependent tunneling characteristics in MTJs. It has recently been shown that x-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD) measurements are powerful techniques for obtaining microscopic information about the element-specific electronic and magnetic states in the interfacial region of MTJs.

Our purpose of the present study is to clarify the electronic and magnetic states of the interfacial region of Co$_2$YZ thin films facing a MgO barrier. For this study, we fabricated epitaxial CMS ultrathin films as typical Co$_2$YZ films with an epitaxial MgO barrier and performed XAS and XMCD measurements at the Mn-$L_{2,3}$ and Co-$L_{2,3}$ edges. To investigate the interfacial region selectively, we fabricated CMS ultrathin films with a 4 ML thickness (=1.1 nm). The fabricated sample layer structure (from the substrate side) was as follows: MgO buffer (10 nm)/Fe underlayer (50 nm)/CMS ultrathin film (1.1 nm)/MgO barrier (2 nm)/Ru cap (2 nm) (hereafter called Fe/CMS (4 ML)/MgO), grown on a MgO(001) single-crystal substrate. The monolayer of Co$_2$MnSi consists of a Co plane and a Mn–Si plane, and a unit cell of CMS, whose lattice parameter is 0.5654 nm (Ref. 10), corresponds to 2 ML of CMS. To stabilize the ferromagnetism of ultrathin CMS films at RT, we grew them on the Fe underlayer. Each layer in the sample layer structure was successively deposited in an ultrahigh vacuum chamber (base pressure: about 6 × 10$^{-8}$ Pa) through the combined use of magnetron sputtering for Fe, CMS, and Ru, and electron beam evaporation for MgO; the fabrication procedure was the same as in previous work. The Fe layer was deposited at RT on the MgO buffer layer, and subsequently annealed in situ at 400 °C. The CMS film deposited at RT was subsequently annealed in situ at 325 °C for 15 min. To ensure no Fe diffusion into the ultrathin CMS film, we used a relatively low annealing temperature of 325 °C based on Ref. 11. Although we did not confirm directly the suppression of Fe diffusion into the CMS films annealed at 325 °C, no signature of Fe diffusion was suggested in the structural or XAS/XMCD evaluations throughout the present study. The pressure during the deposition of the MgO barrier was about 6 × 10$^{-7}$ Pa. The film composition for CMS films used in this study was estimated to be Co$_2$Mn$_{0.91}$Si$_{0.93}$ according to inductively coupled plasma analysis results. As a reference sample, we prepared the same layer structure except that the CMS ultrathin film was intentionally oxidized by exposing it to an O$_2$ atmosphere (~10$^3$ Pa) for 120 min (we refer to this sample as Fe/intentionally oxidized CMS (4 ML)/MgO).

Figure 1 shows reflection high-energy electron-diffraction (RHEED) patterns, along the azimuth of [100]MgO substrate (corresponding to [110]CMS) obtained in situ for each successive layer in the Fe/CMS (4 ML)/MgO layer structure during fabrication. From these RHEED observations, we confirmed that all the layers in the Fe/CMS (4 ML)/MgO grew epitaxially with the (001) basal plane.
Furthermore, we observed 1/2 order superlattice reflections along the [110]CMS direction in the RHEED patterns for the 4 ML CMS film annealed at 325 °C [Fig. 1(b)], indicating that the CMS film had the L2₁ structure.

XAS and XMCD spectra were measured with the total electron yield method using circularly polarized synchrotron radiation at the KEK Photon Factory (BL-11A). The measurements were done at RT. Two XAS spectra for opposite magnetic-field directions (the direction of the magnetic field determines the 3d majority-spin direction) were taken consecutively with the photon helicity fixed. XMCD is defined as the difference between the two spectra with the photon helicity parallel (μ+) and antiparallel (μ−) relative to the 3d majority-spin directions. A magnetic field B (±3 T) strong enough to saturate the sample magnetization was applied perpendicular to the film surface using a superconducting magnet. The degree of circular polarization of incident light was set to 87% (±4%).

Figures 2(a) and 2(b) show XAS and XMCD spectra at the Mn-L₂₃ and Co-L₂₃ edges, respectively, for Fe/CMS (4 ML)/MgO. A small shoulder appeared at the higher photon energy (about 3 eV) side of the Co L₃ peak of the XAS spectrum and a doublent structure appeared in the Mn L₂₃ region in the XAS spectrum. These two features are typical of those for bulk samples or thin films of Co₂MnZ (Z=Si,Ge).6,9,12 In particular, a shoulder at the Mn L₂₃ edge of the XAS spectrum characteristic of full-Heusler alloys with the 3d⁷ electronic configuration assuming a high spin state (Sₜₐ₂ ground state)14 [inset of Fig. 3(a)]. Therefore, we conclude that MnO was formed in the intentionally oxidized CMS (4 ML) thin film. In addition, the XMCD signals at the Mn edges almost completely vanished [Fig. 3(a)], which strongly indicates that the MnO is paramagnetic at RT.

On the other hand, no such multiplet structure appeared in the XAS and XMCD spectra around the Co-L₂₃ edges for the intentionally oxidized CMS (4 ML) film [Fig. 3(b)]. However, the shoulder at the L₃ peak in the Co-edge XAS spectrum characteristic of full-Heusler alloys with the L₂₁ structure disappeared, resulting in a Co-edge XAS L₃ peak slightly narrower in the intentionally oxidized CMS (4 ML) film than that in the CMS (4 ML) film [Fig. 2(b)]. Since the XAS spectrum of Co₇ oxidized exhibited a typical multiplet structure as observed in the MgO substrate/CoO/Fe layer structure [inset of Fig. 3(b)]15 and in the intentionally oxidized 1 ML Co facing an AlOₓ barrier,16,17 the absence of the multiplet structure in the Co-edge XAS and XMCD spectra indicates that no Co oxide existed in the intentionally oxidized CMS (4 ML) film. The narrower L₃ peak in the Co XAS spectrum for the intentionally oxidized CMS (4 ML) film [Fig. 3(b)], however, should be associated with changes in the electronic band structure due to the formation of MnO in the CMS film. Similar XAS spectra indicating the oxidation of Mn atoms and the absence of the oxidation of Co atoms have been reported for the interface between CMS and an AlOₓ barrier.6,9 One possible reason for the oxidation of Mn atoms and the absence of the oxidation of Co atoms is a higher formation enthalpy of MnO (−86 kcal/mol) compared with that of CoO (−51 kcal/mol).5,18

**FIG. 1.** RHEED patterns, along the azimuth of [100]MgO substrate (corresponding to [110]CMS), obtained in situ for each successive layer in the Fe/CMS (4 ML)/MgO layer structure: (a) an Fe underlayer (50 nm) annealed at 400 °C after deposition; (b) a 4 ML (1.1 nm) Co₂MnSi film annealed at 325 °C after deposition; (c) a MgO barrier (2 nm). In (b), 1/2 order superlattice reflections along the [110]CMS direction (arrows) indicate that the CMS 4 ML film annealed at 325 °C grew into the L2₁ structure.

**FIG. 2.** (Color online) XAS and XMCD spectra at the L₃ edges of (a) Mn and (b) Co atoms in fully epitaxial Fe (50 nm)/CMS (4 ML=1.1 nm)/MgO barrier (2 nm).
addition to systematic error in the sum-rule analysis, some structural disorder may exist in the 4 ML-thick CMS film. The $m_{\text{spin}}$ ratio of 2.7 for Mn and Co atoms in the present work is, however, close to a theoretically calculated value of 2.8 (Ref. 22), indicating that the 4 ML-thick CMS film in the present work still maintained the $L_2_1$ structure. The \textit{in situ} RHEED observations also indicated the $L_2_1$ structure for our 4 ML CMS films. The obtained $m_{\text{orb}}$ values of Co and Mn atoms were $0.06 \pm 0.1$ and $0.05 \pm 0.1 \mu_B$, respectively, which are very small. These small $m_{\text{orb}}$ values indicate a quenching of the orbital magnetic moment due to the cubic symmetry. \cite{22}

In summary, the XAS and XMCD spectra observed at the Mn-$L_{2,3}$ and Co-$L_{2,3}$ edges in fully epitaxial layer structures of Fe underlayer/CMOS ultrathin film (4 ML)/MgO barrier directly revealed that the interfacial region of the CMS film facing a MgO barrier was not oxidized. The ratio of 2.7 for the Mn and Co spin magnetic moments obtained through the sum-rule analyses is close to the theoretical value of 2.8 for CMS with the $L_2_1$ structure. The \textit{in situ} RHEED observations also indicated the $L_2_1$ structure for our 4 ML CMS films. These results distinctly show a high-quality interface in CMS films facing a MgO barrier in terms of electronic and magnetic states.

20. I. Galanakis, Ref. 29 in Ref. 6.